THE CONTROL OF IGNEOUS LITHOLOGY ON STEP POOLS IN ALPINE STREAMS: SAN JUAN MOUNTAINS, CO

A Thesis

by

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Submitted to the Office of Graduate and Professional Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

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August 2017

Major Subject: Water Management and Hydrological Science

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ABSTRACT

Step-pool sequences have long been studied in high-gradient streams for the application in erosion control, ecology, and restoration projects. Step-pool sequences are defined as an alternating series of clasts and pools, which self-form to maximize flow resistance. Many studies have been undertaken to identify the main factors that influence formation, but few have taken lithology into account. This study focuses on igneous rocks in the San Juan Mountains surrounding Ouray, CO, to ascertain if igneous-based step pools adhere to the commonly accepted principles governing formation and characteristics of step pools. Based on the data from this study, no strong evidence was found for a correlation between step wavelength and step height. A large percentage of the data supports a correlation between step wavelength and channel width, but a linear prediction model would be inaccurate. The relationship between clast size and step height appears to have a positive correlation for igneous rock, which coincides with much of the existing literature. Step wavelength and reach slope appear to also have a positive relationship. Step steepness does not appear to be related to slope. The correlation increased dramatically after removing outliers from the dataset, but unfortunately a very small sample size was observed.

ACKNOWLEDGEMENTS

I wish to thank everyone that has supported and assisted me throughout this educational journey. To my committee chair, Rick Giardino, for starting with me and sticking through it until the end. To Jack Vitek, for guidance through the final push of the project. To Kevin Gamache, for stepping in on incredible short notice.

To the Water Management and Hydrological Science program for giving me the opportunity to achieve my goal of a master's degree in this program. Thanks also go to the faculty and staff of the Department of Geology and Geophysics Department for setting me on this path.

Finally, thanks to my parents for their love and support throughout this endeavor. Lastly, G, thank you for the guidance and giving me the strength and self-understanding to be who I want to be.

NOMENCLATURE

S	Mean bed slope, measured as height/length
λ_s	Step wavelength, also known as step spacing
H_s	Step height
W_a	Active channel width
W_s	Step width in channel
T_s	Step thickness
Z_s	Step drop height
H_s/λ_s	Step steepness
α	Step-pool aspect ratio (W_a/ Z_s)
LWA	Horizontally level with pool above

CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a thesis committee consisting of John R. Giardino, advisor, and Jack D. Vitek of the Department of Geology and Geophysics and Kevin Gamache of the Department of Water Management and Hydrological Science.

All work for the thesis was completed by the student, under the advisement of Rick Giardino and Jack Vitek of the Department of Geology and Geophysics.

Funding Sources

There are no outside funding contributions to acknowledge related to the research and compilation of this document.

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1. INTRODUCTION

Step pools are defined as alternating series of clasts, or steps, separated by pools (Montgomery and Buffington, 1997). These series are often located in steep valleys with confined channel boundaries (Montgomery and Buffington, 1997). Although a number of studies have been undertaken to determine the processes that form step pools in alpine streams, much remains to understand about the development and characteristics, such as how various factors influence the shape and size.

Terms used to define different measurements of the shape and size of step pools have been introduced over the years. These measurements, shown in Figure 1, include:

λ_s : Step spacing or wavelength

H_s : Step height

S : Mean bed slope

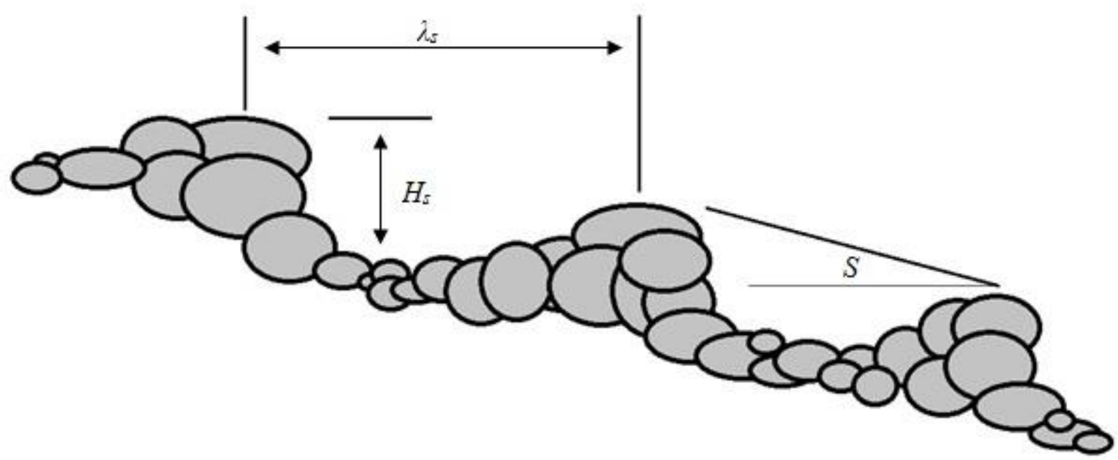

Figure 1 – Diagram of step pools. Diagram showing the longitudinal profile of a step pool sequence.

In the vertical orientation of step pools (Figure 2), several other measurements are shown, including:

W_a : Channel width

W_s: Step width

T_s: Step thickness

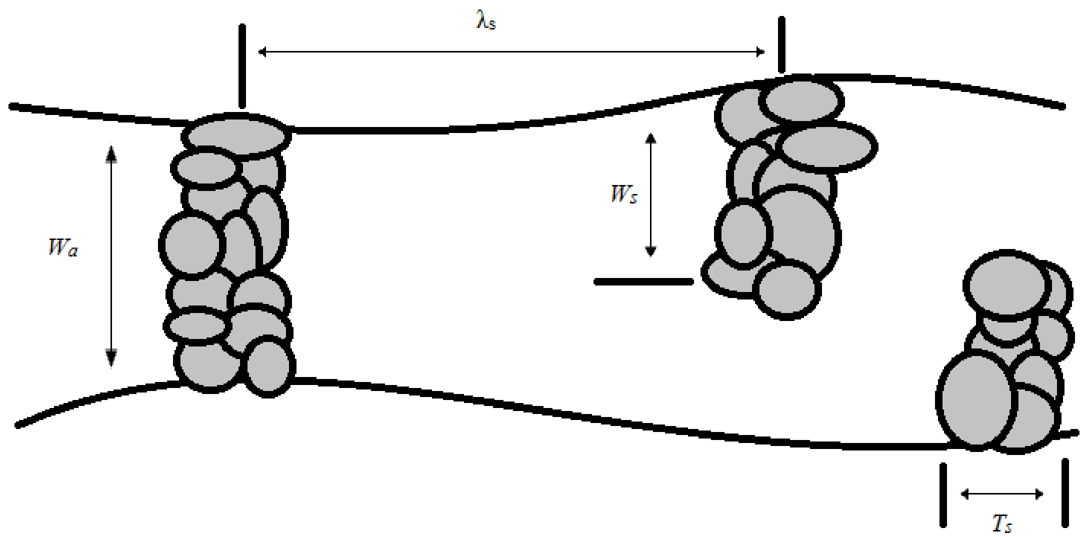

Figure 2 – Vertical diagram of a step pool. Diagram showing the view of a step-pool sequence from above.

1.1 Literature Review

Steps are a way for a stream with a narrow, defined channel to dissipate energy, in what is often considered vertical meanders similar to how horizontal meanders dissipate energy in non-confined channels (Abrahams et al., 1995; Wilcox et al., 2011). This concept of dissipating energy leads to a suggestion by Abrahams et al. (1995) that step pools organize to insure maximum flow resistance. Studies have shown the relationship of grain resistance and wood and flow resistance, showing grain resistance to be minor in comparison (David et al., 2011). Flume studies have illustrated most of the energy dissipation is a result of the loss of potential energy as water falls from the crest of the step to the pool below (Pasternack et al., 2006). An average loss of two thirds of energy has been observed (Wilcox et al., 2011).

Step pools form in a variety of ways, given different properties of the stream in which they are located and the surrounding environment where the stream is located. Several formation models, such as the dune model and rough bed model, seem to be more associated with lower gradient streams that also have smaller particle sizes than higher gradient alpine streams (Curran, 2007). Few formation models directly address larger particle sizes, so formation with particles in the gravel range and above are rarely studied, especially in flume experiments (Curran, 2007; Weichert et al., 2008).

Certain properties of step pools, such as the relationship between gradient and step wavelength, seem to be consistent within a range throughout multiple locations (Chartrand et al., 2011; Chartrand and Whiting, 2000; Chin, 1999a, 2003; Grant et al., 1990; Whittaker, 1987; Wohl et al., 1997), whereas other studies show a very weak correlation (Billi et al., 2014). This correlation proposed by the first group of authors suggests step wavelength is inversely related to slope (Judd, 1963). A reference database compiled by Billi et al. (2014) indicates that this hypothesized inverse relationship is very inconsistent, whereas other studies claim the relationship to be strong (Chin and Phillips, 2007; Chin and Wohl, 2005).

Three main types of flow occur over the step crests in a sequence: skimming, nappe, or a transition between these two (Wilcox et al., 2011). Nappe flow occurs when a free fall occurs from the step crest to the pool below, whereas skimming flow does not have a free fall and the drop is submerged below smooth water (Wilcox et al., 2011). Transitional flow involves nappe flow and includes submerged jets of water that pass through the step (Wilcox et al., 2011). Some contention exists concerning when gradient step sequences will begin to form, but the general consensus is that a slope of 0.02 or greater is required (Billi et al., 1994; Chartrand and Whiting, 2000; Chin, 1999b; Grant et al., 1990; Lenzi, 2001; Maxwell and Papanicolaou, 2004; Montgomery and Buffington, 1997). In addition, various studies have shown that step length tends to decrease with increasing step slope (Chin and Wohl, 2005). The step wavelength also appears to remain in the range of 1-4 channels widths (Chin and Wohl, 2005; Montgomery and Buffington, 1997). Step height is at an average ratio of 1.2 when compared to the size of the particles composing the step (Chin and Wohl, 2005). Woody debris often accentuates step height (Chin and Wohl, 2005; Wohl, 2000). To minimize as many variables as possible, streams with large amounts of woody debris were not considered in this study. An increase in discharge will generally lead to an increase in step spacing as well as increase in the likelihood of skimming flow (Chin and Wohl, 2005).

Throughout the current literature related to step pools, the biggest void is the lack of consistent terms used to describe step pools and the attributes. Many authors use the term "step pool" where others use "pools and riffles" to describe the same form (Grant et al., 1990; Maxwell and Papanicolaou, 2001). No previous studies have investigated if the lithology of the rock composing the steps influence step-pool sequences in any way. The density, hardness, roughness, and composition can vary widely with different lithologies, which could influence some of the other characteristics of step pool sequences, such as step height, step spacing, pool depth, and step width.

1.2 Problem Statement

This study addressed the question: Does igneous lithology impact the characteristics of alpine step pools, such as step height, width, and wavelength?

The working hypothesis for this thesis has been established as:

H_2: Igneous lithology does impact the morphology of step-pool sequences.

H_0: Igneous lithology does not impact the morphology of step-pool sequences.

1.3 Objectives

Two objectives have been established for this thesis:

1) Assess which factor has the most influence on the formation and characteristics of step pools in igneous rocks.
2) Explain the impact of igneous lithology on step pools.

2. STUDY AREA

The San Juan Mountains of southwestern Colorado provide an ideal location to study streams in high gradient areas. The mountains provide an extensive range of lithologies in a small geographical area, however, streams in sedimentary and metamorphic strata are limited in number. For these two reasons, this location has been selected to complete this study with a focus on igneous lithology.

The location of this study is the area surrounding the town of Ouray in the San Juan Mountains of Colorado. The elevation in the area ranges from 2,286 meters to over 3,048 meters, and the study area covers ~150 km^2. Most of the step-pool locations are situated on public land, directly off a main road in many cases. Most of the locations can be accessed by vehicle, with an additional short hike to the ideal reach of the stream that will be analyzed. Figure 3 shows the locations of data collection.

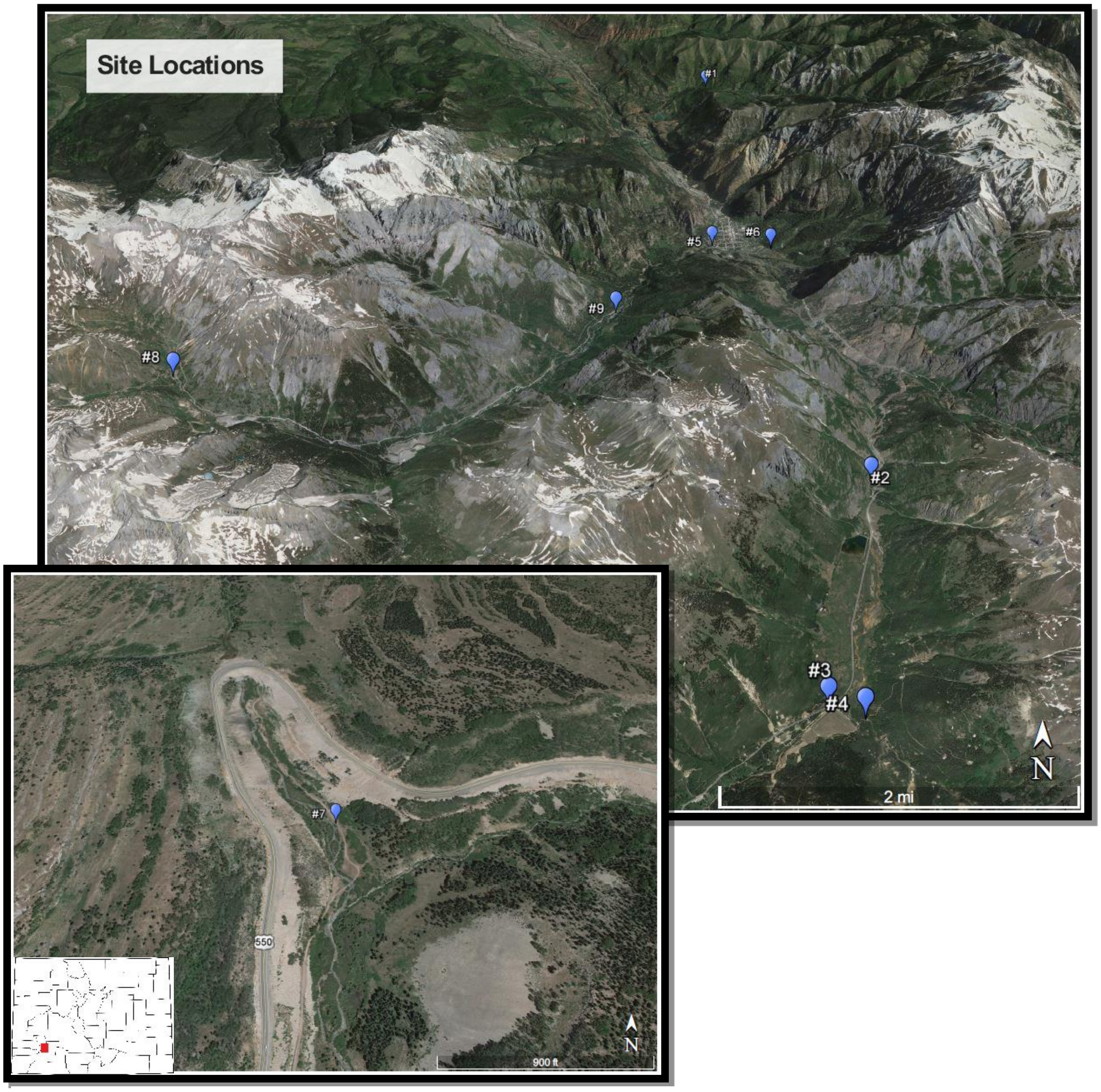

Figure 3 - Map of the study area with locations labeled. (Google, 2016)

The geology and geomorphology of the Ouray area is complex, consisting of various lithologies and landforms. The Uncompahgre River is embedded in a valley train deposit that lines the glacial valley that extends from the south end of Ouray to Ridgeway on the north (Blair and Bracksieck, 2011). Tertiary volcanic deposits, composed of ash and breccia, line the valley along the amphitheater east of Ouray. Glacial moraines appear along U.S. 550 south of town, showing evidence of Pleistocene glaciers (Kelley, 1957). At the locations around sites 3 and 4, lake deposits are found in the valley floor and reveal how a large landslide dammed the Uncompahgre River and formed a lake (Kelley, 1957). Faulting in the area has created unconformities along the boundary between the early phase volcanics and the older Precambrian igneous and Devonian sedimentary units (Kelley, 1957). Avalanches are common in the area because of the presence of steep slopes and lack of vegetation along the rock cliffs (Kelley, 1957). Stretches along the Uncompahgre River within the town of Ouray show quartzite that was metamorphosed during the Early Proterozoic Orogeny (Chronic and Williams, 2002).

Although the geology of the area is varied, with several different lithologies present in a relatively small area, the focus of this thesis is on step pools in only igneous lithology. Kelley (1957) has identified six major façades surrounding the town of Ouray, which will be referenced in the rest of this thesis: Northern, Western, Northeastern, Eastern, Southeastern, and Southern. Each of these has its own unique geology (Kelley, 1957).

The Western Façade is dominated by tall cliffs that rise above the valley. The top of these cliffs consist of the Culter Formation. The lower part of the cliffs extend from the Dolores Formation to the sandstones of the Dakota Formation. All of the sedimentary rocks around Ouray strike 45° to 80° East of North and dip northward (Kelley, 1957).

The central part of the Northern Façade is dissected by two small canyons with the Ouray stock located between the two. This stock is the feeder to the remnants of the laccolith on both sides of Uncompahgre Canyon. Two greenish-grey latite dikes are present in the Hermosa cliffs. The eastern dike continues as a sill along the unconformity at the base of the Dolores Formation (Kelley, 1957).

Southward along the Western Façade, the lower beds are upthrown several hundred meters by the Ouray fault. The upper part of the southern end of the Western Façade is the head of Angel Creek, and it is composed of the San Juan tuff, which is 750 to 900 m thick (Kelley, 1957).

The Northeastern Façade consists primarily of Cascade Mountain. The section here is very similar to the Western Façade, with the Cutler Formation and the Dakota sandstones. The rest of the façade consists primarily of San Juan tuff (Kelley, 1957).

A large crescent-shaped bowl is present along the Eastern Façade. This bowl is locally referred to as The Amphitheater. The bowl consists of San Juan tuff, which has an exposed thickness of 900 meters. The lower slopes are composed of landslide material, which covers what is assumed to be glacial moraines underneath. Elevations on either side of the Amphitheater exceed 3,000 m (Kelley, 1957).

The Southeastern Façade is a rounded, bold ridge that is located south of the Amphitheater. The foreground is composed of Ouray Limestone that rises only a few hundred meters above the valley floor. Behind this ridge is a low, bold ridge composed mostly of Precambrian quartzite of the Uncompahgre formation, whereas the upper part is composed of San Juan tuff.

The Southern Façade faces Hayden Mountain, which is situated between Uncompahgre Canyon to the east and Canyon Creek to the west. Several topographic steps occur south of town. The first step is composed of Devonian and Mississippian Ouray limestone. The second step is largely quartzite that strikes westerly and dips steeply northward. Some of the most striking geology along the Southern Façade is found along the Ouray fault. This fault is nearly vertical and the maximum downthrow is several hundred meters along the middle section of the fault. The difference in the strengths of the cementation of the beds on both sides of the fault has created a bold scarp, which has a waterfall present from spring through fall (Kelley, 1957).

The valley was formed from a combination of stream and glacial erosion, as well as mass movement (Chronic and Williams 2002).

The weather of the southern San Juan Mountains consists of snowfall in the winter and convectional afternoon thunderstorms in the summer. Snowmelt in the spring leads to an increase in water discharge as shown in Figure 4.

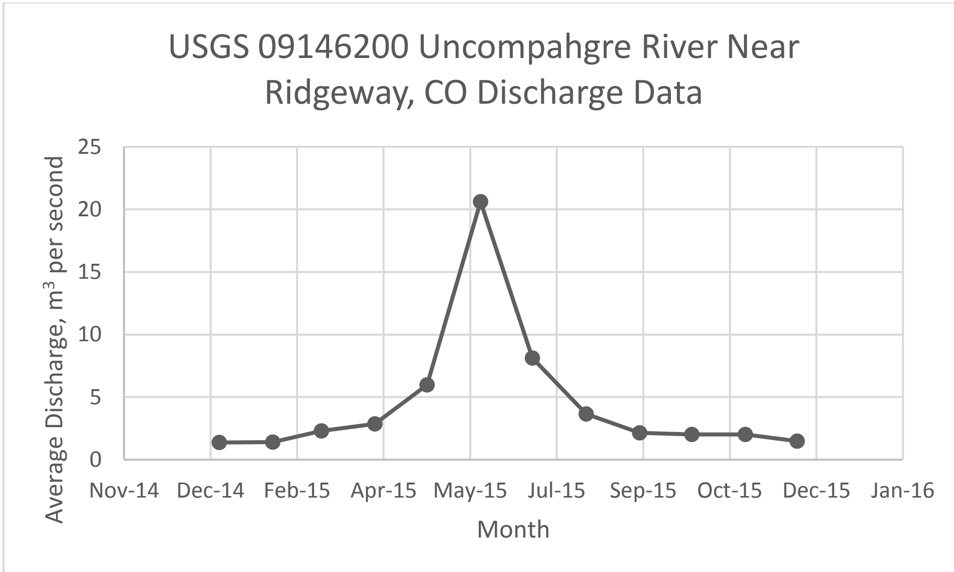

Figure 4 – USGS stream gauge data showing peak discharge during spring snow melt (USGS, 2016).

Temperatures range from average lows of -9°C in the winter to average high temperatures of 24°C in the summer (WRCC, 2016). Temperatures can be highly varied and can range from below freezing to over 16°C in a day (Blair and Bracksieck, 2011). Average temperature is shown in Figure 5 below.

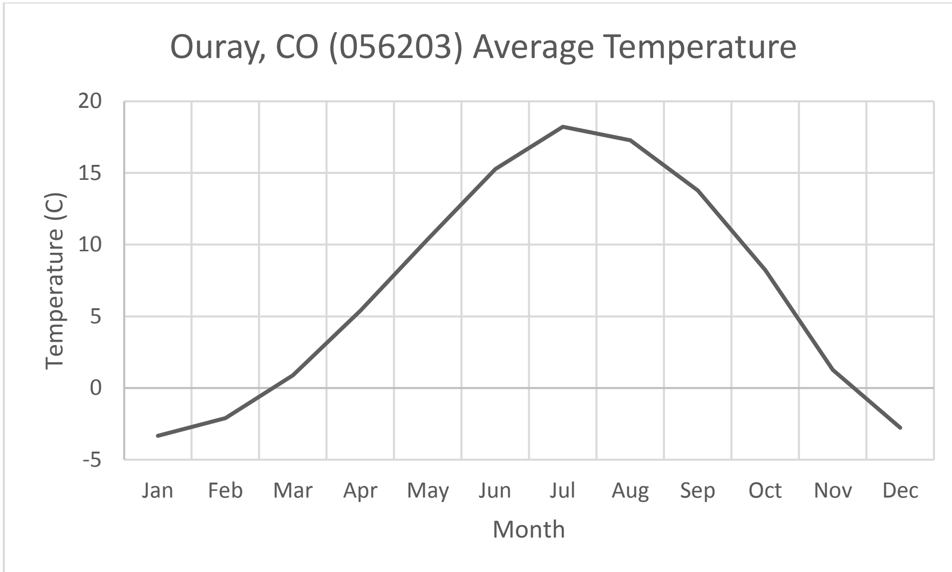

Figure 5 - Average temperature for Ouray, CO, from 1948-2005 (WRCC, 2016).

Average precipitation is shown in Figure 6 and consists of data from 1948-2005. Comparing the river discharge and precipitation shows even though less total precipitation occurs in the late spring, discharge is still high from snowmelt.

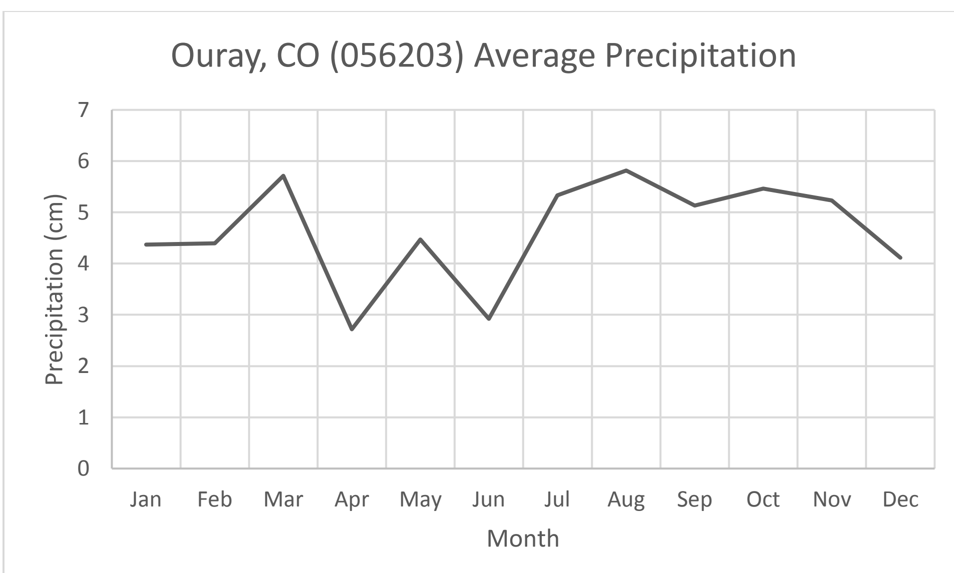

Figure 6 – Average precipitation for Ouray, CO, from 1948-2005 (WRCC, 2016).

3. METHODOLOGY

The methodology explains the process taken from data collection to analysis, which enabled the objectives to be met. The first objective of determining if a governing factor has the most influence on the formation and characteristics of step pools was accomplished by the following:

1) The first step involved a reconnaissance of the Ouray, CO, area to identify possible locations where step pools are associated with igneous lithologies. Geologic maps of the area were studied and numerous possible locations were identified, which were then examined in the field.
2) After potential locations were identified, a plan to sample and measure each location was established.
3) Each day in the field consisted of hiking to the suitable locations previously identified, then following the stream path downhill along a step-pool sequence.
4) As progress was made downstream, measurements of channel width and step spacing were made using a conventional tape measure and stadia rod.
5) Each step pool in the sequence had its height, thickness, and width measured. The channel width, and the sizes of the clasts creating the steps as well as the clasts located in the pool were also measured. The average slope of the step-pool sequence was taken using an Abney level from the first step to the last step in the measured sequence. A GPS location was created to later pinpoint the location of the sequence.

6) Samples from each of the steps were taken to determine the lithology of the step and more specific notes were taken to indicate other important characteristics of the location such as the inclusion of woody debris, or other abnormal properties.
7) In the lab, the collected data were compiled in Microsoft Excel® and analyzed to determine the most important influence on the characteristics of the steps using several statistical methods, including sample ANOVA, mean, linear and exponential regression, and correlation with significance tested to 90%.
8) After the data collected were compiled and analyzed, a manuscript addressing the effect of igneous lithology on the formation and characteristics of step pools was produced.

Once the steps are completed, the second objective of explaining the impact of igneous lithology on step pools was addressed. Using either linear or exponential regression, best-fit lines were produced as well as correlation coefficients for important ratios.

4. DATA AND ANALYSIS

The step-pool sequences have been divided into three categories based on lithology: igneous, metamorphic, and sedimentary. Seven igneous sequences were measured with an average of six steps per sequence. Because of the dominant presence of igneous rock in the study area, only one sequence of metamorphic and sedimentary were observed, with five and eight steps present in each sequence, respectively. The list of locations and corresponding lithologies are given in Table 1.

Location	**Stream Name**	**Lithology Present**
1	Dexter Creek	Igneous
2	Uncompahgre River	Igneous
3	Red Mountain Creek	Igneous
4	Gray Copper Gulch	Igneous
5	Uncompahgre River	Metamorphic
6	Portland Creek	Igneous
7	Lime Creek	Sedimentary
8	Sneffels Creek	Igneous
9	Canyon Creek	Igneous

Table 1 – Shows the stream names of different locations and the dominant lithology present.

Slope has shown in many studies to be a determining factor in several characteristics of step pools. Judd (1963) and Whittaker (1987) have each given calculations for fitting slope to the wavelength of a step pool. These formulas are shown in (1) and (2), and the results as compared to the measurements of slope taken in the field shown in Table 2 for igneous, Table 3 for sedimentary, and Table 4 for metamorphic, respectively.

$$\text{(1) Whittaker: } \lambda_S = {}^{0.3113}/_{S^{1.188}}$$

$$\text{(2) Judd: } \lambda_S = {}^{1}/_{2S}$$

Location	Average Slope	Judd's Calculation	Whittaker's Calculation
1. Dexter Creek	0.06	0.06	0.06
2. Uncompahgre River	0.07	0.05	0.05
3. Red Mountain Creek	0.04	0.05	0.06
4. Gray Copper Gulch	0.05	0.06	0.06
6. Portland Creek	0.05	0.12	0.11
8. Sneffels Creek	0.12	0.14	0.13
9. Canyon Creek	0.10	0.09	0.09

Table 2 – This table shows the measured slopes for each igneous location compared to the slopes based on the formulas derived by Judd and Whittaker (Judd, 1963; Whittaker, 1987).

Location	Average Slope	Judd's Calculation	Whittaker's Calculation
7. Lime Creek	0.05	0.05	0.05

Table 3 - Slope by location for sedimentary.

Location	Average Slope	Judd's Calculation	Whittaker's Calculation
5. Uncompahgre River	0.05	0.03	0.04

Table 4 - Slope by location for metamorphic.

The step wavelength in relation to channel width and step height are shown in Table 5 for igneous, Table 6 for sedimentary, and Table 7 for metamorphic, respectively.

Location	Step Wavelength /Channel Width	Step Wavelength/Step Height
1. Dexter Creek	3.43	8.97
2. Uncompahgre River	1.42	5.28
3. Red Mountain Creek	0.96	13.24
4. Gray Copper Gulch	2.09	11.19
6. Portland Creek	4.61	8.20
8. Sneffels Creek	0.95	5.81
9. Canyon Creek	0.55	14.86
Average Values	2.00	9.63

Table 5 – Step wavelength/channel width and step wavelength/step height by location.

Location	Step Wavelength /Channel Width	Step Wavelength/Step Height
7. Lime Creek	1.10	14.44

Table 6 - Step wavelength/channel width and step wavelength/step height for sedimentary rock.

Location	Step Wavelength /Channel Width	Step Wavelength/Step Height
5. Uncompahgre River	1.02	9.12

Table 7 - Step wavelength/channel width and step wavelength/step height for metamorphic rock.

The data in Table 8 show an average of the determining ratios of step-pool sequences by each lithology. This is not an average of the sequences because some of the step-pool sequences have more steps than others, and more sequences occur on some lithologies than others.

	Igneous	Sedimentary	Metamorphic
Step Wavelength/ Step Height	9.63	14.45	9.12
Step Wavelength/ Channel Width	2.33	1.10	1.02
Step Height/ Clast Size	1.39	1.38	1.43
Step Wavelength/ Reach Slope	174.6	277.7	400.0
Step Steepness/ Reach Slope	2.95	3.19	1.97

Table 8 - Important average ratios for each lithology.

5. RESULTS AND DISCUSSION

5.1 Relationship between step wavelength and step height

Several studies have shown a significant correlation between step spacing and step height (Chartrand and Whiting, 2000), whereas other studies do not support this same findings (Nickolotsky and Pavlowsky, 2007; Wooldridge and Hickin, 2002). For step pools formed in igneous lithology in this thesis, strong evidence for a correlation is lacking for step wavelength and step height, as shown in Figure 5 with an $R^2 = 0.18$.

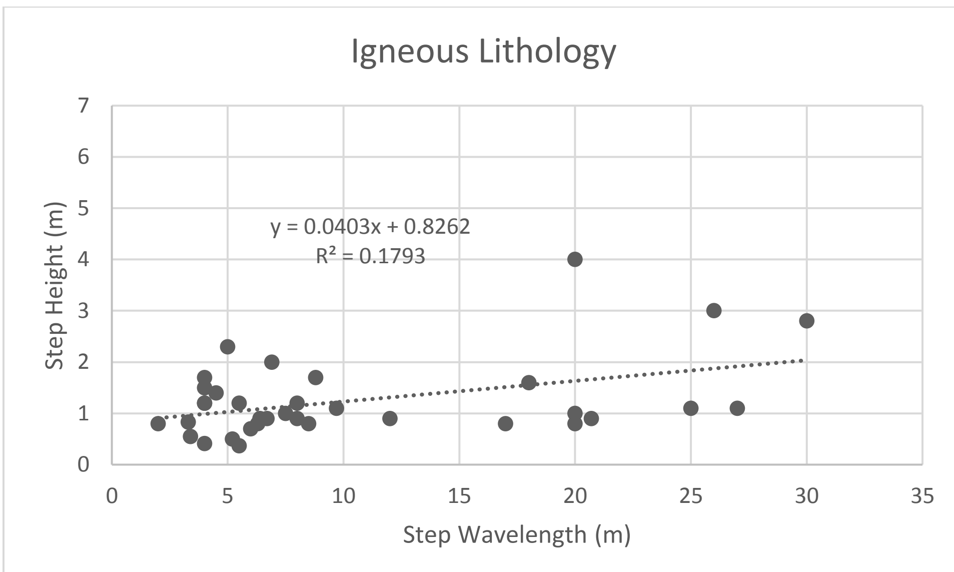

Figure 7 – Step height related to step wavelength for igneous lithology.

5.2 Relationship between step wavelength and channel width

Several authors have suggested a relationship between step wavelength and channel width (Billi et al., 2014; Chartrand and Whiting, 2000; Chin, 1999b; Gomi et al., 2003; Grant et al., 1990; Whittaker, 1987; Wohl et al., 1997). A reference database compiled by Billi et al. (2014) suggests that 67% of data for the ratio of step wavelength/channel width lies within the range of 0.5 to 1.5 with an average of 1.3. The igneous dataset from this study shows an average ratio of 2.3 and a range of 0.4 to 13.9, which lies outside the projected range. However, 86% of the data lies within the range of 0.4 to 3.8, which brings the ratio to 1.4. The metamorphic and sedimentary datasets have ratios of 1.0 and 1.1, respectively, but unfortunately come from a small sample size. Figure 6 shows the igneous lithology with linear and exponential trendlines. Very low correlation coefficients indicate that specific prediction for step wavelength based on channel width does not exist.

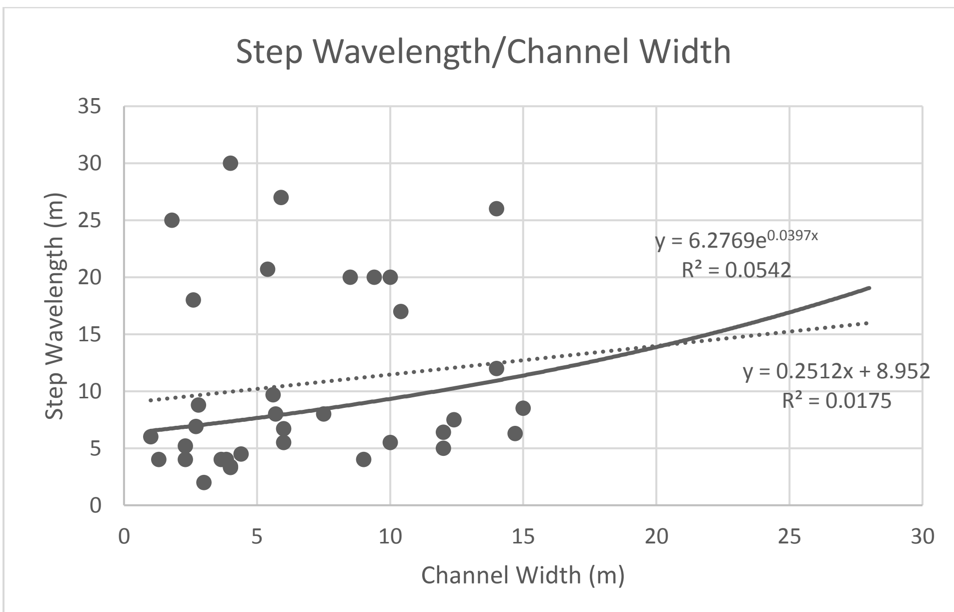

Figure 8 - Step wavelength/channel width for igneous lithology.

5.3 Relationship between step clast size and step height

Several studies have shown step height to be dependent on the size of the clasts composing the step, such as the flume experiments carried out by Curran and Wilcock (2005). The reference database compiled by Billi et al. (2014) appears to confirm this hypothesis, showing a correlation coefficient of $R^2 = 0.64$. The study also carried out by Billi et al. (2014) shows a slightly lower correlation (R2 =0.59) from their study site on the Aneva River. Other studies have shown, however, a much weaker correlation between these characteristics (Nickolotsky and Pavlowsky, 2007). The dataset from igneous lithology from this thesis appears to confirm a positive relationship between step height and step clast size with a significant strong correlation of $R^2 = 0.91$. The igneous dataset from this study with the best fit trendline is shown in Figure 9.

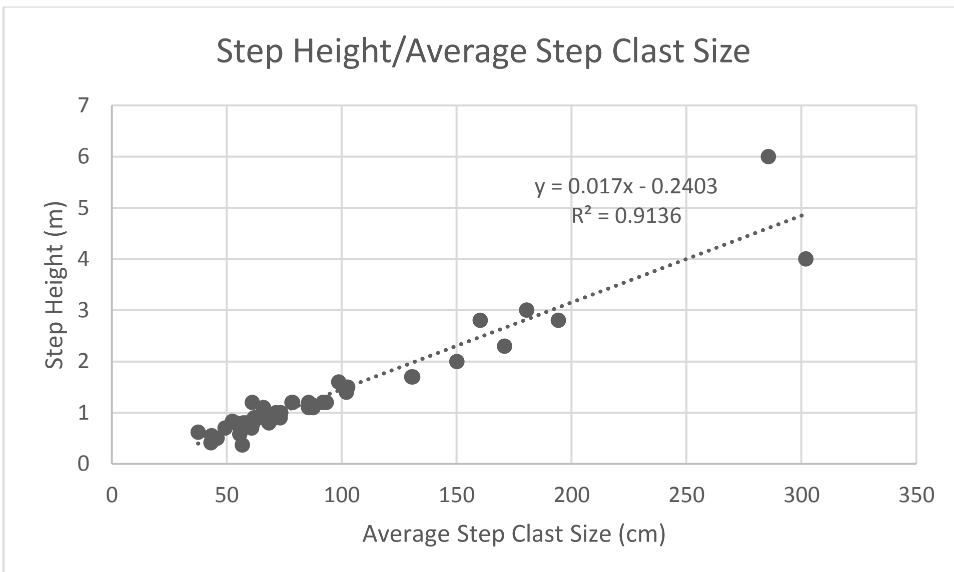

Figure 9 - Step height and step clast size relationship for igneous lithology.

5.4 Relationship between step wavelength and reach slope

For this thesis an exponential trendline was created using Judd's formula for comparing step wavelength to reach slope. Because the slope data that were measured were a total for the entire sequence, the average wavelength was compiled for each sequence and plotted against the measured slope. The correlation coefficient was determined to be $R^2 = 0.57$, which is a stronger correlation than Chin's (1999a) correlation coefficient of $R^2 = 0.33$. Other studies have demonstrated no relationship between slope and step wavelength, including a compilation of a reference database from multiple studies (Billi et al., 2014).

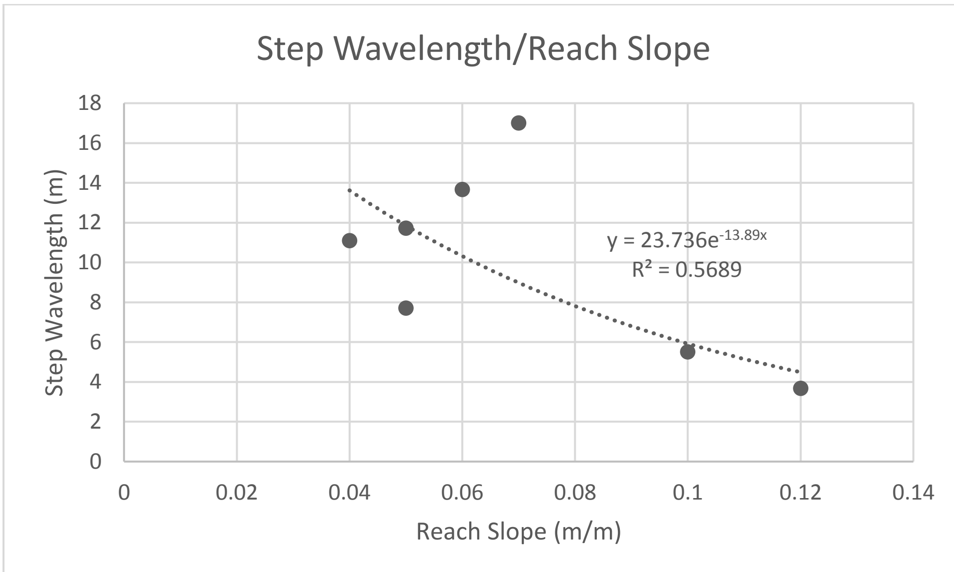

Figure 10 - Step wavelength compared to reach slope for igneous lithology.

5.5 Relationship between step steepness and reach slope

Numerous authors have identified an inverse relationship between step steepness (step height/step wavelength) and slope (Abrahams et al., 1995; Chartrand and Whiting, 2000; Grant et al., 1990; Judd, 1963; Whittaker and Jageggi, 1982). Weichert et al. (2008) illustrates that most datasets lie within the ratio of $(H_s/\lambda_s)/S = 1$ and $(H_s/\lambda_s)/S = 2$, which is based on the flume experiments by Abrahams et al. (1995) that show maximum flow resistance is reached when that ratio is between 1 and 2. For this dataset, the average steepness over reach slope is 2.95, which does not fit within the normal guidelines proposed by (Abrahams et al., 1995). Over 60% of the datasets compiled by Billi et al. (2014), however, lie within the 1 to 2 range of the ratio. An attempt to fit an exponential trendline to the data from this thesis shows a very low correlation coefficient (Figure 11). When removing a single outlier, however, the correlation value increases to $R^2 = 0.55$ from the original value of $R^2 = 0.09$, and demonstrates significance. Once again, for these data the average step steepness from the entire sequence was compared to the reach slope, as slope measurements between each steps individually was not measured.

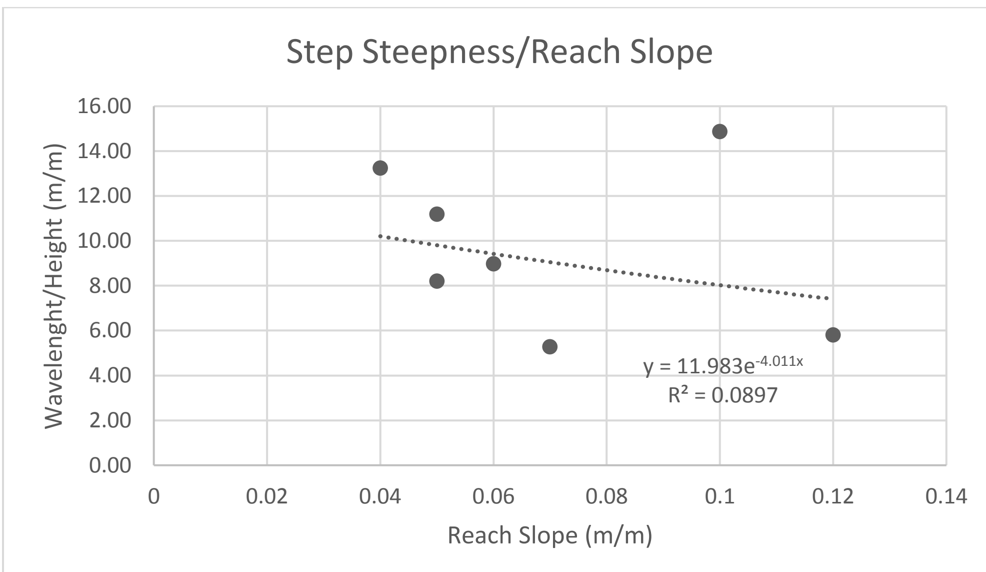

Figure 11 - Slope steepness compared to reach slope for igneous lithology.

6. SUMMARY AND CONCLUSIONS

Step pools are common in confined channels with steep slopes. This thesis has utilized the abundance of step-pool sequences in the area surrounding Ouray, CO, to analyze step pools in the igneous lithology. This thesis indicates that several factors of step-pool sequences within igneous lithology are correlated.

For this thesis, my primary objective was to explain the impact of igneous lithology on step pools. Within igneous lithology, no distinguishable correlation occur between step wavelength and step height. A significant positive relationship exists between step wavelength and channel width. For igneous lithology, a very strong significant correlation exists between clast size composing the step, and the height of the step. Wavelength and reach slope appear to also have a significant positive correlation. Step steepness as compared to slope seems to have a significant positive correlation after an outlier was removed from the dataset, but a specific prediction for each factor is unlikely to be accurate because of the large variance. My objective of assessing which factor has the most influence on the formation and characteristics of step pools determined step clast size to have the greatest impact on step-pool sequences in the igneous lithology.

Future studies should focus on other lithologies to compare to the data from this thesis, to determine possible differences across lithologies. Slope from step to step as opposed to slope across the entire reach would also add statistical power to the ratios concerning slope from this thesis.

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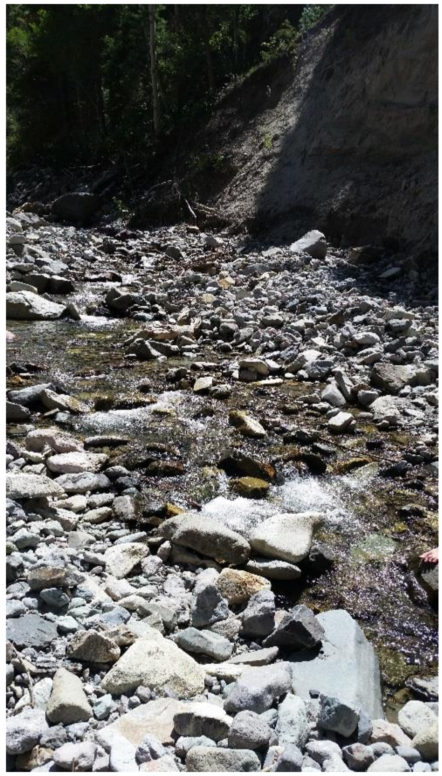
APPENDIX

Site 1 – Dexter Creek – August 2015

Step	Step Height (M)	Step Spacing (M)	Step Thickness (M)	Step Width (M)	Channel Width (M)
1	1.7	8.8	1	2.8	2.8
2	0.9	8	2	7.5	7.5
3	1.2	4	0.6	9	9
4	2.8	30	2.5	4	4
5	1.6	18	1	2.6	2.6
6	1	20	1	8.5	8.5
7	2	6.9	3	2.7	2.7
8	1.2	N/A	2.1	3	3



Site 2 – Uncompahgre River – August 2015

Step	Step Height (M)	Step Spacing (M)	Step Thickness (M)	Step Width (M)	Channel Width (M)
1	2.3	5	2.5	12	12
2	3	26	4	14	14
3	4	20	6	10	10
4	6	N/A	7	28	28

Site 3 – Red Mountain Creek – August 2015

Step	Step Height (M)	Step Spacing (M)	Step Thickness (M)	Step Width (M)	Channel Width (M)
1	0.8	6.3	1	2.5	14.7
2	0.8	8.5	0.7	3	15
3	0.9	12	0.5	2.4	14
4	0.8	17	0.9	5	10.4
5	0.9	6.4	0.7	7.8	12
6	0.8	20	2.3	6	9.4
7	1	7.5	2.5	8	12.4
8	1.2	N/A	1.1	10.6	10.6

Site 4 – Gray Copper Gulch – August 2015

Step	Step Height (M)	Step Spacing (M)	Step Thickness (M)	Step Width (M)	Channel Width (M)
1	1.1	9.7	LWA	5.6	5.6
2	1.2	8	LWA	5.7	5.7
3	0.9	20.7	LWA	5.4	5.4
4	0.9	6.7	LWA	6	6
5	1.1	27	LWA	5.9	5.9
6	1.2	5.5	1.7	6	6
7	1.4	4.5	LWA	4.4	4.4
8	0.7	N/A	LWA	5.3	5.3

Site 5 – Uncompahgre River – August 2015

Step	Step Height (M)	Step Spacing (M)	Step Thickness (M)	Step Width (M)	Channel Width (M)
1	2.7	13	2.4	20	20
2	2	8	3	19	19
3	1.8	36	LWA	19	19
4	3	23	4	20.7	20.7
5	2.7	N/A	LWA	24.5	24.5

Site 6 – Portland Creek – August 2015

Step	Step Height (M)	Step Spacing (M)	Step Thickness (M)	Step Width (M)	Channel Width (M)
1	1.7	4	1.8	1.3	1.3
2	1.5	4	2.7	2.3	2.3
3	0.5	5.2	3.3	2.3	2.3
4	0.8	2	LWA	3	3
5	1.1	25^	LWA	1.8	1.8
6	0.7	6	LWA	1	1
7	2.8	N/A	5	1.5	1.5

Site 7 – Lime Creek – August 2015

Step	Step Height (M)	Step Spacing (M)	Step Thickness (M)	Step Width (M)	Channel Width (M)
1	0.8	20	LWA	5	14
2	0.9	23.5	LWA	3.4	11.5
3	1.1	8	LWA	11	11
4	1	19	2	6.4	12.3
5	1	6	1.8	7	12
6	1.3	7.7	1.7	10	13
7	1.1	13	LWA	7.6	15.5
8	1.7	N/A	2	15	15

Site 8 – Sneffels Creek – August 2015

Step	Step Height (M)	Step Spacing (M)	Step Thickness (M)	Step Width (M)	Channel Width (M)
1	1.2	4	LWA	3.86	3.85
2	0.83	3.3	0.79	4	4
3	0.55	3.4	0.9	2.27	4
4	0.41	4	0.72	1.5	3.65
5	0.62	N/A	0.6	2	2

Site 9 – Canyon Creek – August 2015

Step	Step Height (M)	Step Spacing (M)	Step Thickness (M)	Step Width (M)	Channel Width (M)
1	0.37	5.5	1	10	10
2	0.58	N/A	LWA	9	9